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Studying the Propagation of Detonation Waves Through Explosive Objects

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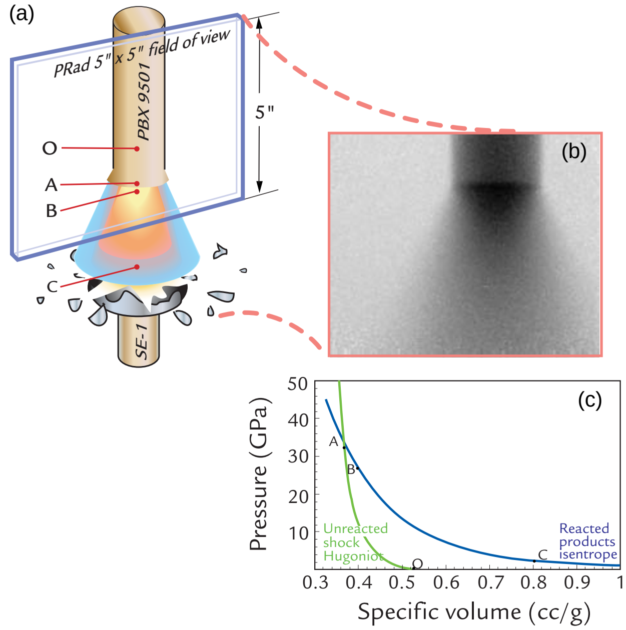
High explosives (HEs) are energetic materials engineered to release their stored energy when a strong pressure shock propagates across the material. Once the energy is released, the pressure built up by the process supports the propagation of the shock wave. The synergistic combination of the shock-wave stimulus and the subsequent support of the shock from the release of energy is called a detonation wave. We conducted a set of explosive experiments using the multiple-frame capability of proton radiography (pRad) to test simple explosive configurations, to explore the kinematic evolution of the detonation waves, and to obtain density measurements from proton beam attenuation. The explosive systems used in our pRad experiments were detonated in a containment system, which is designed to allow the viewing of the proton-transmission image of the experiment at the scintillator location through a magnetic lens system.[1] The containment system is evacuated to reduce blurring. The static image, the beam profile, and the camera dark current along with the dynamic images are used to obtain normalized images of the proton transmission along its path length. All of the images discussed in this research highlight are of exploding objects that are axially symmetric, allowing us to make density measurements at various stages of the dynamic evolution of the system. In these pRad experiments, we are learning what is required to make the best possible measurements of radiographic transmissions. The results of the density and velocity measurements will be compared to computer-calculated codes.

We have performed several detonation-wave-propagation experiments on three configurations—each one with a different regime of the detonation-wave propagation. The first configuration, known as the "rate-stick experiment," is the steady propagation of a detonation wave through a cylindrical charge in which this wave reaches a steady state that only depends on the diameter and material of the charge. The second configuration, the "wave-collider experiment," involves the head-on collision of two detonation waves in which strong shock waves are reflected back into the explosive products. The third configuration, the "corner-turner experiment," examines the propagation of a steady detonation wave down a small-diameter charge entering a larger-diameter charge. Ultimately, the detonation wave in the larger-diameter charge travels faster than in the small-diameter charge. Upon initial entry into the large charge, however, the wave has insufficient energy support to initiate the explosive, leaving behind a shocked, but mostly unreacted, explosive.

Rate-Stick Experiment

Rate-stick charges are used for the measurement of the steady detonation velocity in cylindrical charges and its variation with charge radius and initial conditions.[2] We have used PBX9501 and PBX9502 rate-stick charges in the pRad 0079 and pRad 0080 experiments. The detonation wave shown in Fig. 1b has already reached steady propagation, having traveled more than 10 cm before the wave had entered the field of view. By measuring the positions of the initial wave front at different times, we found that the detonation wave was propagating at a constant velocity of 8.83 mm/μs. We can make better density estimates of the explosive products by averaging translated images and subsequently reducing the radiographic noise in the images as is shown in Fig. 1b. Ultimately, this information will be compared to computer-calculated kinematics of the wave propagation. Also, the experimental density, as obtained from the attenuation of the proton beam, will be compared to the computer-calculated density.

A simplified thermodynamic view of this experiment is shown in Fig. 1c. The initial material state, **O**, is shocked to state **A** on the Hugoniot curve of the unreacted material. (A Hugoniot is the locus of thermodynamic states achievable behind a shock wave

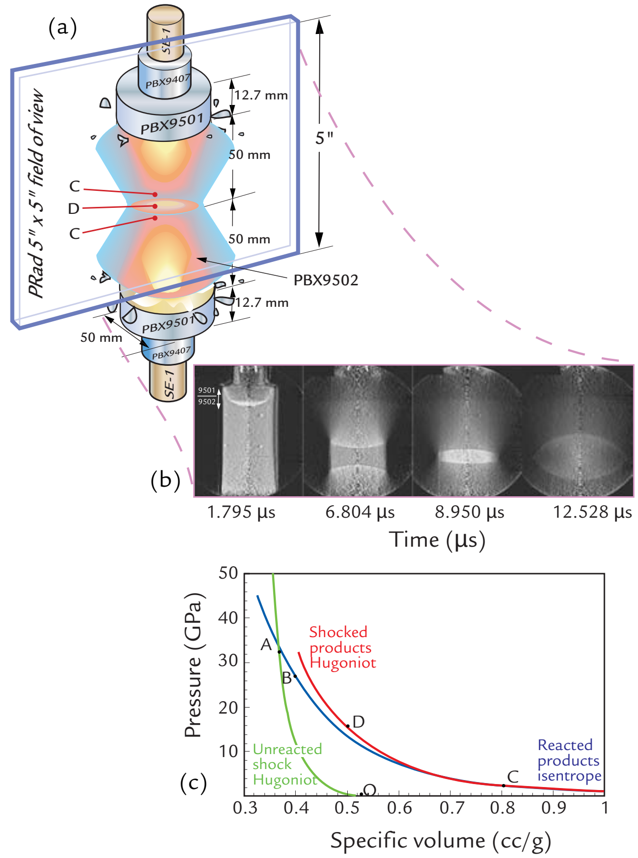


↑ Fig. 1. *(a) Artist's rendering of the rate-stick experiment. The SE-1 is a detonator used to initiate the explosive (PBX9501) under study. The PBX9501 cylinder was 8 in. long and 0.5 in. in diameter, although the experiment view encompassed only the last 4.5 in. of the dynamic event. (b) The average of seven translated radiographs results in a sharper image over a limited region. The image darkness is proportional to the length of material the proton beam had to pass through. The dark band propagating along the charge is the detonation wave, and the conical structure that follows is the release of high-pressure reaction products. (c) A simplified thermodynamic view of the pressure-volume processes going on in the rate-stick experiment: initial state material, O, is shocked to state A on the Hugoniot curve, which initiates a reaction that occurs between states A and B. The hot products then expand taking materials to lower density (at C) along the isentrope.*

from a given initial state **O** without reactions taking place.) The reaction then takes place from state A to state B. From state B, the reaction products expand along what is called the release isentrope in which the hydrodynamic flow proceeds at constant entropy. Although we have no direct measurement of the pressure in this experiment, we can validate the thermodynamic relations used in the calculations by comparing the calculated densities to the experimental ones. Although the release isentrope reveals much information about the thermodynamics of the reaction products, it is insufficient to specify its equation of state. To describe the products at any accessible pressure and volume, we must determine what happens to them as they deviate from the isentrope. We accomplished this in the wave-collider experiment described in the next section.

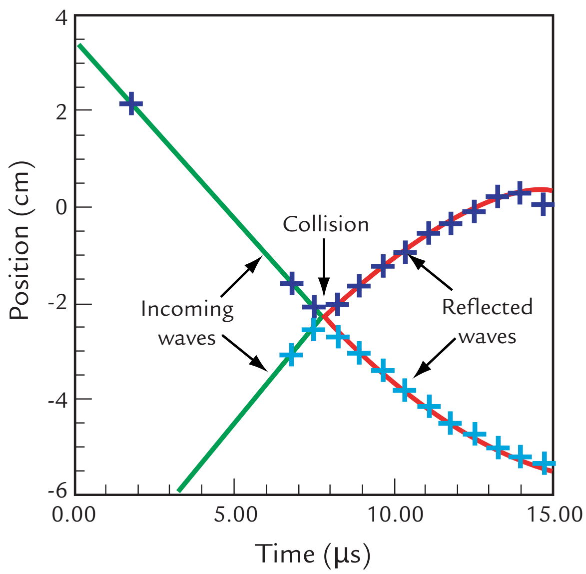
Wave-Collider Experiment

The wave-collider experiment (Fig. 2) allowed us to examine the shocked reaction products at various

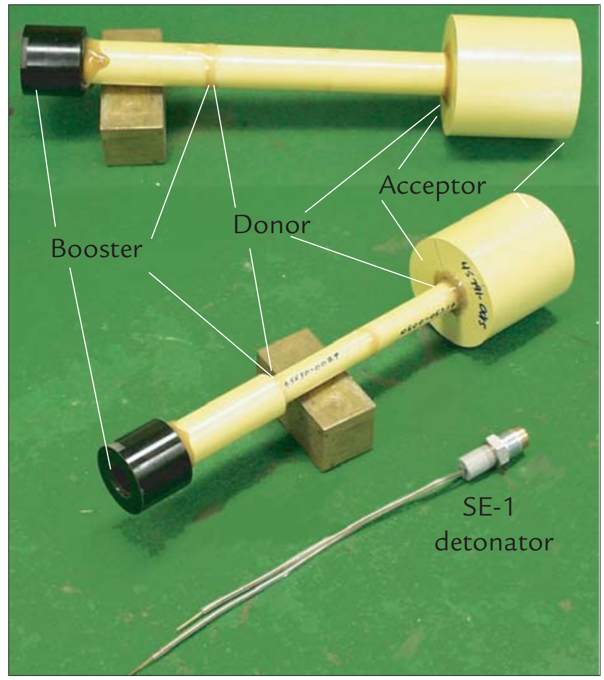


↑ Fig. 2. *(a) Artist's rendering of the wave-collider experiment. The wave collision occurs within the PBX9502 charges. The PBX9501 and PBX9407 charges are booster charges required to efficiently initiate the less-sensitive explosive. (b) Volume-density images found from the radiographs taken of the experiment (assuming that the exploding objects are axially symmetric). (c) Thermodynamic states reached in the wave-collider experiment. State D lies on the shocked products Hugoniot for state C. Each image after the reflection reveals a different pair of C and D states lying on distinct Hugoniot curves.*

densities on the release isentrope. In this experiment, we examined one detonation wave in PBX9502 running into an identical detonation wave propagating in the opposite direction. Like the rate-stick experiments, these results are also cylindrically symmetric; however, in this experiment, the speed of the steady detonation wave is not achieved, the wave not having traveled a sufficient number of diameters in length. Furthermore, because the reflected shock waves do not propagate into a uniform state, their subsequent propagation into the reflected products is not steady state. Four of the analyzed radiographs are shown in Fig. 2b. Assuming that the exploding objects are axially symmetric, our analysis resulted in a measurement of the material density behind the shock waves. In Fig. 3, the leading edge of the detonation wave is examined. The waves approach the center at about 7.3 mm/µs. The shock waves then reflect outward initially at almost



↑ ***Fig. 3.*** *Shock-wave trajectories from the wave-collider experiment. The two incoming shock waves have velocities of 7.2 and 7.4 mm/µs. The reflected shocks rebound out into the products, initially at nearly 7 mm/µs but at less than 5 mm/µs after 2 µs.*



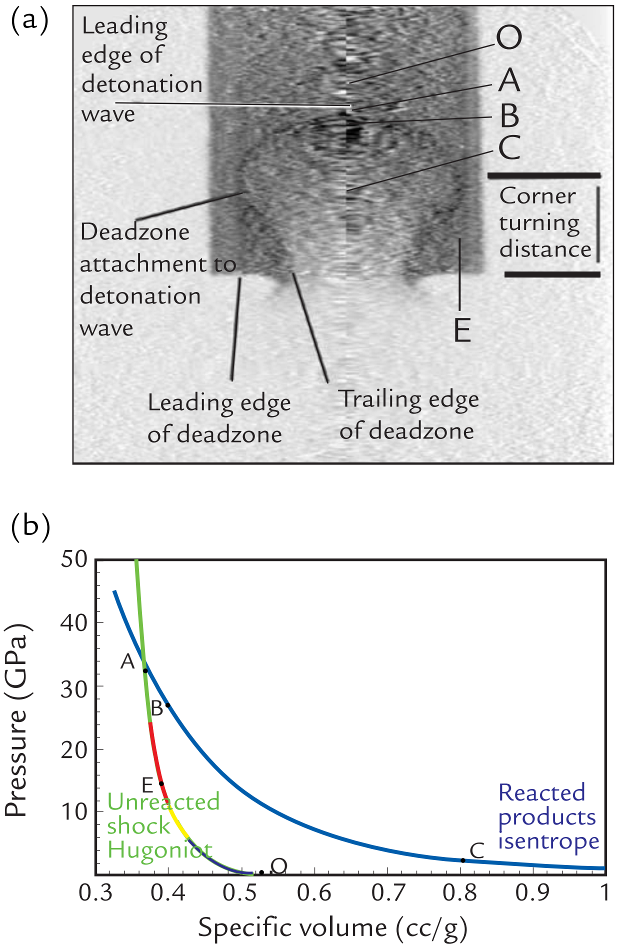
↑ ***Fig. 4.*** *Corner-turning charges made from PBX9502.*

7 mm/µs but then quickly slow down to 5 mm/µs after 2 µs. By the end of the observation, the shock velocity is down to 2 mm/µs. The wave positions plotted in Fig. 3 are measurements made in the experimental frame of reference, so the shock waves that have material movement ahead or behind them may be stronger than the velocity might indicate. The pressure-volume diagram (Fig. 2c) adds a new curve, the *shocked products Hugoniot*, indicating that expanded products at state C are shocked without reactions, thus taking them to a new state D. Initial estimates on shock-wave compressions would indicate about a 15% volume compression in the incoming detonation wave, which takes unreacted explosives from an initial density of 1.9 g/cc (state O) to about 2.2 g/cc (state A) of reaction products. As the wave travels away from the center where the products have been allowed to expand for a longer period of time, the density ahead of the shock is reduced to 0.8 g/cc, and the density behind the shock is reduced to about 1.1 g/cc, or 30% compression at the end of the experiment.

Corner-Turning Experiments

The goal of the PBX9502 corner-turning experiments is to study the initiation and boosting requirements of insensitive explosives. Previous uses of this experiment have identified differences in materials with subtle changes in their microstructures. The experimental configurations in Fig. 4 show two of the charges used for this work. The charges consist of three sections: an initiation/booster charge, a smaller-diameter donor charge, and a larger-diameter acceptor charge. Earlier experiments observed the time of first arrival of the shock along the cylindrical surface of the acceptor charge.[3] With an ideal HE, the detonation wave will reach the outside cylindrical surface at the donor-acceptor plane. The further away the first arrival is from the acceptor donor plane, the more difficulty the donor charge has initiating the acceptor and the less ideal the explosive behaves. In Fig. 5a, the density image shows the detonation wave front having propagated well into the large section of the charge. In our case, the detonation-wave front breaks out at the side of the charge near the point marked "corner-turning distance," thus demonstrating the non-ideal behavior of PBX9502. Also seen in the image is a high-density region in the acceptor, which the detonation wave apparently had to travel around.

The high-density region is denser than the initial HE material and persists in the later images. This region where the shock is not strong enough to initiate the material is called a deadzone. The leading edge of the deadzone expanded radially at about 3.3 mm/µs, whereas the trailing edge expanded about 0.9 mm/µs. As the wave enters the larger-diameter acceptor charge, the surface area of the detonation wave increases rapidly at the corner, resulting in a pressure drop in the divergent flow. With the lack of support, the detonation wave fails to maintain the reaction resulting in material that is shocked but does not



↑ ***Fig. 5.*** *(a) Volume-density image of the 12-mm corner-turner experiment at 25.3 μs. The regions called out in the image identify the deadzone. (b) Representative states in the radiograph have been identified in our thermodynamic pressure-volume description. State E in the deadzone region has not been shocked sufficiently to cause a fast reaction. Material shocked into the red portion of the unreacted shock Hugoniot will accelerate to state A in 0.25 μs to 1.0 μs, assuming a well-supported one-dimensional shock wave. In this case, the support is not sufficient and the reaction falters.*

react.[4] In Fig. 5b, we see that two very different regions occur. The first is a successful detonation like in the rate-stick experiment—the shock and reaction move the system from state O to A, then to state B, and finally releases to state C. The second region, the deadzone, is quite different because the divergent flow in the corner cannot support a strong enough shock, resulting in a shock taking the system from state O to state E well below state A and resulting in a region of nearly no reaction.

Conclusion

We have studied three facets of detonation-wave propagation using pRad to examine the kinematic evolution and density distributions of the flow. The rate-stick experiment resulted in a steady detonation wave and the reacted material occurring on the release isentrope. The wave-collider experiment examined fully detonated material off of the release isentrope by reflecting a shock wave back into the products. The corner-turning experiment examined some material shocked so weakly that the reaction failed to proceed. Although simple in configuration, these experiments show the synergistic relations between the release of chemical energy in the explosive and the shock waves, which trigger the chemical reaction.

References

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